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On analytical models of optimal mixture of mitigation and adaptation investmentst☆

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ABSTRACT

Determining the optimal combination of mitigation and adaptation investments is an important topic in policy making to combat climate change. Some analytical results on the relationship between the optimal ratio of adaptation to mitigation and development level have been reported in the literature. In this article, we examine this relationship in greater detail using a simple model with general return functional forms and analytically show that the relationship can take various forms. The results suggest a desirable design of empirical studies on adaptation measures. In addition, the insights obtained in the simple model are useful to understand more complicated models.

1. Introduction

Adaptation, the importance of which was recognized later than that of mitigation, has acquired a prominent place in policy making on climate change. A possible reason for the rising attention to adaptation is that people are more aware of that climate change damage cannot be altogether avoided or that international cooperation for combating climate change is difficult (Tol, 2005). The Conference of the Parties 21st Session to the UN Convention on Climate Change (COP21), which was held in 2015, recognized an increasing role for adaptation and emphasizes the benefits of cost reductions for adaptation efforts. New York City's Flexible Adaptation Pathways and the Climate Smart Adaptation of the Queensland Climate Change Centre of Excellence are famous examples of adaptation efforts at the regional level.

The growing attention on the topic has demanded studies on various topics concerning adaptation. Though we do not intend to be exhaustive here, the literature includes a number of case studies that have been accumulated and have clarified feasibility of adaptation options, costs and benefits of each option, and practical issues in implementation (see, for example, Berrang-Ford et al., 2015). Other works analyze the implication of adaptation to the sustainability of international cooperation (Zehaie, 2009; Ebert and Welsch, 2012; Heuson et al., 2015). de Bruin et al. (2009) and de Bruin (2011) add an adaptation decision to the DICE model, which is an Integrated Assessment Model (IAM), and examined how adaptation interacts with mitigation decisions in balancing between developing climate change strategies and maintaining healthy economic activities. Barrage (2015) focus on the fiscal revenue effects of mitigation and adaptation options and discuss implications in the context of optimal taxation.

Adaptation aims to reduce the vulnerability of social systems and offset the effects of climate change. Compared to mitigation, adaptation is conducted at geographically and politically smaller scale (Buob and Stephan, 2011). The advantage and disadvantage of adaptation to mitigation arise from this feature. The advantage is that adaptation in each region can independently provide benefits private to regional societies and thus the free-riding is less problematic. The disadvantage is the difficulty in monitoring adaptation activities. The variety and case-specificity of adaptation activities require a lot of efforts for comprehensive evaluations (Tol et al.,

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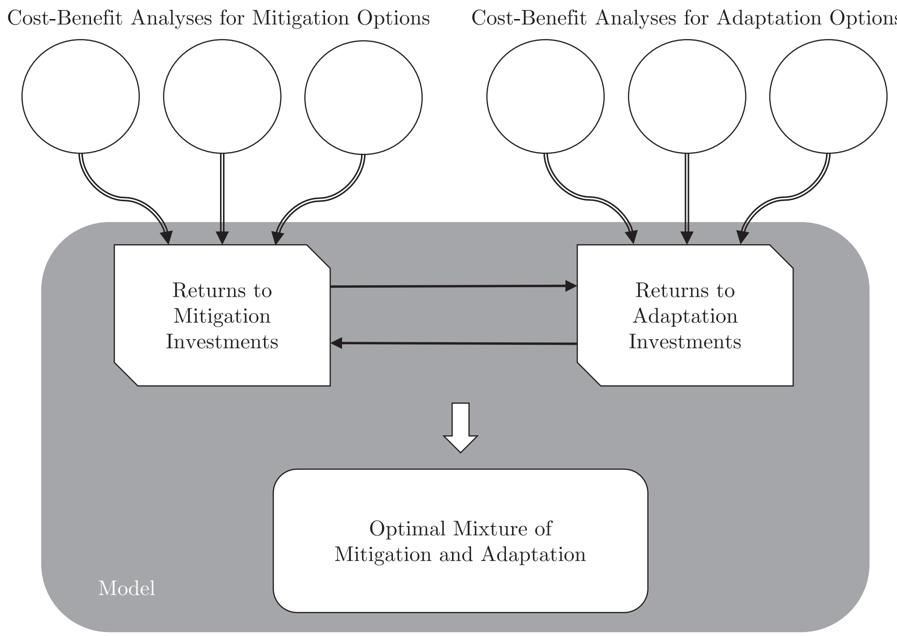

Fig. 1. Research framework.

1998).

Previous works in the literature have been working on how to allocate limited resources between mitigation and adaptation investments. This work aims to contribute to the literature by examining the allocation problem, drawing a unified understanding of previous results in the literature, and suggesting a design of empirical works for achieving a more socially desirable mixture of mitigation and adaptation investments. Fig. 1 describes the framework of our research. The shaded area indicates the model of mitigation and adaptation investments that we analyze. We analytically examine how properties of returns to mitigation and adaptations affect the optimal mixture of the two types of investments. This part is depicted by the white arrow at the center of the shaded area in the figure. Based on the results of the analysis, we make suggestions about a desirable design of cost-benefit analyses of mitigation and adaptation options, which are the source of empirical evidence about returns to mitigation and adaptation investments.

In this article, we examine the relationship between the optimal ratio of adaptation investment to mitigation investment, which has been analyzed in the literature, in greater detail. First, we formulate a simple static model of mitigation and adaptation investments with general return functional forms in Section 2. The model includes a parameter capturing the amount of available resources for mitigation and adaptation, which we interpret as the level of development. The objective function is assumed to take a multiplicative form to capture the feature of the mitigation-adaptation investment problem whereby an increase in a given mitigation measure decreases the necessity of adaptation, and vice versa. The multiplicative form can endogenously arise in some specific contexts, as we discuss in Section 4, and should be understood as a crude way to incorporate the feature into the model in other contexts.

Our model is very simple. For example, compared to the model in Bréchet et al. (2013), our model is abstracted from dynamics, stock nature of pollution, and economic production activities. Relative to Ingham et al. (2013), ours does not take strategic interaction among countries or uncertainty into account. Compared to Zemel (2015), our model does not consider dynamics, stock nature of pollution, and uncertainty. These comparisons are summarized in Table 1. The advantage of the simplicity is the high tractability of the model, which allows us to analyze the relationship more intensively than what has been done in the literature. In addition, as we discuss below, insights from our model are applicable to those more structured models.

Our main result is reported in Section 3. After showing that an equation determines the optimal ratio, using the equation, we analytically prove that the relationship can exhibit various patterns: any function in a wide class can yield the optimal ratio if we appropriately select a pair of return functions. Note that all functional forms for mitigation and adaptation returns that are included in the class satisfy reasonable assumptions, in that they are monotonic and have diminishing marginal returns. To demonstrate the breadth of the range of potential functions, we present several examples. The examples demonstrate that the optimal ratio can be (i) constant, (ii) monotonically increasing, (iii) monotonically decreasing, (iv) U-shape, (v) Inversed U-shape, or (vi) more complicated patterns.

Although our model is static and extremely simple, the insight from the examples is useful to understand more complicated models, such as that of Bréchet et al. (2013). In Section 4, we show the optimal ratio in the model of Bréchet et al. (2013) is determined by an equation similar to that in our simple model. Then, we provide examples in which various patterns that are similar to the examples in our model arise. We also relate our result to Zemel (2015). In his model, the multiplicative form arises endogenously and, therefore, offers an interpretation of the multiplicative form of utility functions. We show that the optimal ratio is characterized similarly in Zemel (2015).

In Section 5, we discuss qualitative features of the return functions and relate them to empirical evidence. Cost-benefit analyses provide information about returns from adaptation investments and constrain qualitative features of the adaptation return function.[1] We also discuss the relationship between our result and the

[1] See ECONADAPT (2015) and Watkiss (2015) for a review of cost-benefit analyses for adaptation projects.

Table 1
Comparison of our model to related works in the literature; A check mark in a column indicates that the corresponding work considers the corresponding model ingredient.

	Dynamics	Pollution stock	Production	Uncertainty	Strategic interaction
Bréchet et al. (2013)	✓	✓	✓		
Ingham et al. (2013)				✓	✓
Zemel (2015)	✓	✓		✓	

IAM models that include adaptation strategies, such as the AD-DICE and the AD-WITCH models.

Our result re-emphasizes the importance of collecting empirical evaluations of costs and benefits of mitigation and adaptation measures, which is far from new and repeatedly highlighted in the literature (e.g., IPCC, 2007). Unless we know the functional form of mitigation and adaptation return functions, we cannot determine the optimal division of resources. Our result indicates that it is unlikely that calibration can solve the problem, unless a quite wide class of return functions, which have many parameters, is employed. Calibrating such parameters would also require further empirical evidence. As discussed in Agrawala (2011), empirical work is at present limited to specific sectors and areas. A recommendation drawn from our results is that we should make more efforts for collecting comprehensive information on costs and benefits of adaptation projects and, in particular, that they should be estimated for various levels of mitigation investments. By so doing, we will be able to avoid inefficient use of resources due to ignoring the interaction of mitigation and adaptation: an increase in a mitigation measure decreases the necessity of adaptation, and vice versa.

1.1. *Literature review*

The origin of the literature of analytical approaches to mitigation and adaptation investments goes back to the work of Shibata and Winrich (1983). Kane and Shogren (2000), which analyzes the problem with uncertainty, is another early work in this literature. Ingham et al. (2013) show that, in a variety of simple mitigation-adaptation investment problems, the two measures are substitutes. Zemel (2015) focuses more on the dynamic aspect of the problem and relates the optimal timing of beginning investments in adaptation measures to the amount of existing pollution stocks. Bretschger and Valente (2011) examine how adaptation efficiency interacts with economic growth and show that poor countries are likely to be hurt more, because of faster depreciation of capital assets due to climate change. Bréchet et al. (2013) explore the relationship between the level of production efficiency and the efficient share of adaptation relative to mitigation. They report an analytical result that an economy with very low productivity should engage in mitigation only and that the optimal ratio of adaptation investment to mitigation investment increases as productivity increases up to a threshold level, beyond which the ratio decreases under a specific set of functional forms.

The approach through IAMs started to take adaptation into account recently, after the call by Tol and Fankhauser (1998), who found through their survey that most of IAMs had not considered adaptation explicitly then. One exception is the work of Hope et al. (1993), which is a pioneer in this literature. Using the PAGE model, they evaluate adaptation policy assuming that it will reduce damage by up to 90%. The estimated cost is 0.5 trillion Euro, while the estimated benefit is 17.5 trillion Euro. These estimates have been criticised for being inconsistent with empirical evidence on costs and benefits of adaptation (for example, see Mendelsohn, 2000). Tol (2007) incorporate adaptation for coastline protection into the FUND model and estimate the damage avoided by mitigation and adaptation in this specific sector. de Bruin et al. (2009) develop the AD-DICE model, is a version of the DICE model with explicit adaptation policy choice. They explore the feature of the optimal policy and show that it is a mixture of mitigation and adaptation and that adaptation is the main force of damage reduction until 2010 while mitigation replaces it thereafter. Bosello et al. (2010) propose the AD-WITCH model which includes flow adaptation, stock adaptation, and adaptation capacity. They examine the difference between OECD and non-OECD countries in the composition of adaptation types based on calibrated results in their model. Agrawala et al. (2010) compare results from a version of the AD-DICE which distinguish short-term temporary (flow) and long-lined capital intensive (stock) adaptation with those from the AD-WITCH model. de Bruin (2011) analyzes the interaction of stock and flow adaptation in the AD-DICE and conduct an intensive sensitivity analysis. Felgenhauer and Webster (2014), in their variation of the AD-DICE model, analyze how the optimal ratio of investments into the two types of adaptation and mitigation depends on the model parameters.

2. Model

The model can be thought of as a simplified version of those in Bréchet et al. (2013), Zemel (2015), and Ingham et al. (2013). There is an exogenous resource $Y > 0$ that can be used for mitigation $B \geq 0$ and adaptation $D \geq 0$:

$$B + D \leq Y. \tag{1}$$

Allocations are evaluated by an avoided damage,

$$-\eta(D)g(B), \tag{2}$$

where $\eta : [0,\infty) \to (0,\infty)$ and $g : [0,\infty) \to (0,\infty)$ are functions that determines how much mitigation and adaptation can reduce damage from climate change. We assume that η and g are both strictly decreasing, meaning that mitigation and adaptation are intrinsically beneficial. Although this model abstracts from why mitigation and adaptation are beneficial, it is nevertheless useful for understanding more structured models, such as that of Bréchet et al. (2013), as discussed in Section 4. The multiplicative form is a simple but crude way to capture an important property of the mitigation-adaptation investment problem: an increase in mitigation investment decreases the necessity of adaptation investment, and vice versa. In this formulation, we essentially assume that marginal return to mitigation is $-\eta(d)g'(B)$ and that to adaptation is $-\ \eta'(d)g(B)$. Even with such a simplifying assumption, the relationship between the optimal ratio and the amount of resources exhibits various patterns, as we show later.

The planner's problem is to maximize (2) subject to (1), $B \geq 0$, and $D \geq 0$. We assume that η and g are continuously differentiable and log-convex: $\log\eta(D)$ and $\log g(B)$ are convex. Moreover, we assume that one of them is strictly convex. This is a sufficient condition for the strict concavity of the objective function and simplifies the analysis. The differentiability should be thought of as a rough approximation of the reality, and the log-convexity might be unreasonable assumption. The point of our analysis is that even though restricting the class of return functions with these potentially

unreasonable assumptions, the resulting relationship between the optimal share and the amount of resources can take various forms. If we do not assume these two conditions, the class of resulting relationship between the optimal share and the amount of resources will include more various forms of the relationship.

3. Solution

The following lemma summarizes the characterization of the solution.

Lemma 1. *Let (B^*, D^*) denote the optimal solution for the planner's problem. Then,*

1. $(B^*, D^*) = (Y, 0)$ *if and only if* $-\frac{\eta'(0)}{\eta(0)} \leq -\frac{g'(Y)}{g(Y)}$.
2. $(B^*, D^*) = (0, Y)$ *if and only if* $-\frac{\eta'(Y)}{\eta(Y)} \geq -\frac{g'(0)}{g(0)}$.
3. (B^*, D^*) *is interior and characterized by*

$$-\frac{\eta'(D^*)}{\eta(D^*)} = -\frac{g'(B^*)}{g(B^*)}, \tag{3}$$

$$B^* + D^* = Y. \tag{4}$$

if and only if $-\frac{\eta'(0)}{\eta(0)} > -\frac{g'(Y)}{g(Y)}$ *and* $-\frac{\eta'(Y)}{\eta(Y)} < -\frac{g'(0)}{g(0)}$.

The Proof is a standard application of the Karush-Kuhn-Tucker condition, and hence, it is omitted. In the following, let $D^*(Y)$ and $B^*(Y)$ denote the optimal adaptation and mitigation to emphasize that they are functions of the exogenous resource parameter Y.

Lemma 1 is useful to analyze how the optimal ratio of adaptation to mitigation $R(Y) = D^*(Y)/B^*(Y)$ moves as the amount of resource Y varies, which is our main interest.

Example 1. (Increasing ratio with boundary solution). Suppose that the return functions are given by

$$g(B) = B^{-\theta},$$

$$\eta(D) = e^{-aD},$$

where $\theta > 0$ and $a > 0$ are parameters. The functions g and η satisfies all of the assumptions, and we can apply Lemma 1. The optimal ratio is given by

$$R(Y) = \begin{cases} 0 & \text{if } 0 < Y \leq \theta/a, \\ \dfrac{Y - \theta/a}{\theta/a} & \text{if } \theta/a < Y < \infty. \end{cases}$$

Fig. 2 depicts the function $R(Y)$ when $\theta = 5$ and $a = 1$.

The next example is based on the work of Bréchet et al. (2013).

Example 2. (**Ratio increasing for low level and decreasing for high level**). The return functions are given by

$$g(B) = B^{-1},$$

$$\eta(D) = \underline{\eta} + \left(\overline{\eta} - \underline{\eta}\right)e^{-aD},$$

where $\underline{\eta} > 0$, $\overline{\eta} > 0$, and $a > 0$ are parameters that satisfy $\underline{\eta} < \overline{\eta}$. This pair of functions are taken from Bréchet et al. (2013). The function g and η satisfy all the assumptions. By Lemma 1, as long as $0 \leq Y \leq \frac{\underline{\eta} + (\overline{\eta} - \underline{\eta})}{a(\overline{\eta} - \underline{\eta})}$, the optimal adaptation is at the boundary $D = 0$,

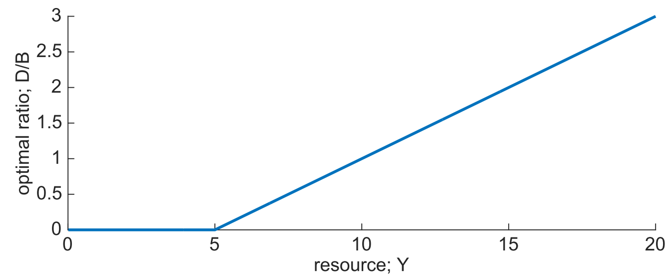

Fig. 2. Optimal ratio $R(Y)$ in Example 1.

and for $Y > \frac{\underline{\eta} + (\overline{\eta} - \underline{\eta})}{a(\overline{\eta} - \underline{\eta})}$, the solution is interior and characterized by

$$D^* + \left[\frac{a\left(\overline{\eta} - \underline{\eta}\right)e^{-aD^*}}{\underline{\eta} + \left(\overline{\eta} - \underline{\eta}\right)e^{-aD^*}}\right]^{-1} = Y.$$

To our knowledge, this equation does not allow any explicit solution, and we cannot obtain any explicit solution for $R(Y)$. Computing numerically, we can obtain the optimal ratio function $R(Y)$. The result for $\underline{\eta} = 10$, $\overline{\eta} = 100$, and $a = 1$ is depicted in Fig. 3.

Our main interest concerns how the optimal ratio of adaptation to mitigation $R(Y)$ moves as the amount of resource Y varies. As in Example 2, an explicit solution is sometimes unavailable, and that is inconvenient to explore the relationship between the optimal ratio and the amount of resources. We can nevertheless investigate it in the following way. Define $F_g : [0, \infty) \to \mathbb{R}$ and $F_\eta : [0, \infty) \to \mathbb{R}$ by

$$F_g(B) = -\frac{g'(B)}{g(B)},\ F_\eta(D) = -\frac{\eta'(D)}{\eta(D)}.$$

Then, by Lemma 1, the ratio can be expressed as

$$R(Y) = \frac{D^*(Y)}{F_g^{-1}(F_\eta(D^*(Y)))}.$$

Define also

$$\widehat{R}(D) = \frac{D}{F_g^{-1}(F_\eta(D))}.$$

Then, if D^* is differentiable,

$$\frac{dR(Y)}{dY} = \frac{d\widehat{R}(D^*(Y))}{dD}\frac{dD^*(Y)}{dY}.$$

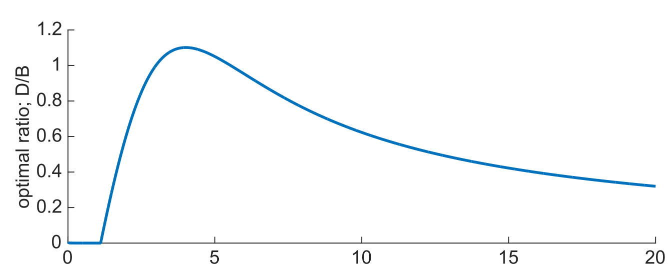

Fig. 3. Optimal ratio $R(Y)$ in Example 2.

Because $D^*(Y)$ is strictly increasing, the sign of dR/dY is the same as that of $d\widehat{R}/dD$. Therefore, we can investigate the slope of R by investigating the slope of $\widehat{R}$, whose analytical expression is readily available.

Using the result above, we can obtain the following proposition, which states that the optimal ratio, as a function of the amount of resources, can exhibit various patterns.

Proposition 2. *For any continuously differentiable function $\widehat{r}:(0,\infty)\to(0,\infty)$ such that $\int_0^\infty \frac{\widehat{r}(D)}{D}dD<\infty$ and for any $D\in(0,\infty)$ such that $\widehat{r}'(D)/\widehat{r}(D)<1/D$ holds, there exists a pair of continuously differentiable, strictly decreasing, and strictly log-convex functions (g,η) such that*

$$\widehat{r}(D)=\frac{D}{F_g^{-1}(F_\eta(D))}$$

holds.

The Proof is in the Appendix.

Roughly speaking, the message of the proposition is that any functions $\widehat{r}$ that satisfy the inequality conditions are the optimal ratio of adaptation to mitigation in the planner's problem under some pair of return functions (g,η). The class of functions that satisfies the inequality conditions is wide; For example, any nonincreasing function is included in the class. Therefore, the proposition indicates that the relationship between the optimal ratio and the amount of resources can take various forms.

For other examples, see the Appendix, which shows various patterns of the change in the optimal ratio caused by productivity change: (i) constant, (ii) 0 (which means that the solution is at the boundary $D=0$) for low productivity and increasing for high productivity, (iii) infinity (meaning that the solution is at the boundary $B=0$) for low productivity and decreasing for high productivity, (iv) increasing for low productivity and decreasing for high productivity, (v) decreasing for low productivity and increasing for high productivity, (vi) monotonically increasing, and (vii) monotonically decreasing.

What does the result mean? The most important implication is that the assumptions, that returns are increasing and have diminishing marginal returns and that an increase in mitigation investment decreases the necessity of adaptation investment, and vice versa, do not say much about how the optimal investment ratio is related to the available resources. In other words, the relationship depends on the details of the shape of the return functions, for which there is little empirical evidence.

To know the shape of the return functions, we need to collect costs and benefits of adaptation and mitigation projects. In an ideal situation in which we possessed information on costs and benefits of all adaptation and mitigation projects of the world, we could obtain the shape of the return functions just by arranging those projects in descending order of benefit-cost ratio. It is apparently impossible in the reality. To achieve a more socially desirable mixture of mitigation and adaptation investments, we need to make efforts for collecting more comprehensive information on costs and benefits of adaptation projects. In particular, they should be estimated for various levels of mitigation investments to avoid inefficient use of resources due to ignoring the interaction of mitigation and adaptation: an increase in a mitigation measure decreases the necessity of adaptation, and vice versa.

This discussion is applicable to more complicated models. If a model has similar multiplicative forms, an equation similar to Equation (3) characterizes the optimal investment ratio, as we show in the next section.

4. Relating the result to more complicated models

The model in this article is extremely simple, but the insights are useful to understand more complicated models. To demonstrate this point, first, we show the optimal ratio is characterized by a similar equation to that in the model of Bréchet et al. (2013). Then, we provide examples in which various patterns that are similar to the examples in the Appendix arise. We also show that the same equation characterizes the optimal ratio in Zemel (2015), noting how the multiplicative form arises endogenously.

4.1. Bréchet et al. (2013)

Time is continuous and indexed by t. The horizon is infinite. There is a consumption good that can be converted into production capital or adaptation capital. At each moment t, the planner observes production capital $K(t)$, adaptation capital $D(t)$, and the pollution stock $P(t)$. Production capital $K(t)$ produces $AK(t)^\alpha$ units of the consumption good as output, where $A>0$ is a productivity parameter. In this model, because production is endogenous, the parameter A is the exogenous parameter that determines resource availability. We interpret A as the level of development. The planner must determine how to use the output. It can be used for production capital investment $I_K(t)$, adaptation capital investment $I_D(t)$, mitigation effort $B(t)\geq 0$, or consumption $C(t)\geq 0$:

$$AK(t)^\alpha=I_K(t)+I_D(t)+B(t)+C(t). \tag{5}$$

The evolution of production and adaptation capital is standard:

$$\dot{K}(t)=I_K(t)-\delta_K K(t),\quad \dot{D}(t)=I_D(t)-\delta_D D(t), \tag{6}$$

where $K(0)$ and $D(0)$ are given and $\delta_K\geq 0$ and $\delta_D\geq 0$ are depreciation parameters. The law of motion of the pollution stock is given by

$$\dot{P}(t)=AK(t)^\alpha g(B)-\delta_P P(t), \tag{7}$$

where $P(0)$ is given, $\delta_P\geq 0$ is a depreciation parameter, and $g:[0,\infty)\to[0,\infty)$ is a decreasing function. Here, $g(B)$ determines the rate of pollution emission from production activity. The more mitigation effort B is made, the less pollution is emitted. The planner evaluates allocations by

$$\int_0^\infty e^{-\rho t}U(C(t),P(t),D(t))dt \tag{8}$$

where $\rho>0$ is discount factor, U is given by

$$U(C,P,D)=\log C-\eta(D)\nu(P),$$

where $\eta:[0,\infty)\to[0,\infty)$ and $\nu:[0,\infty)\to[0,\infty)$ is a strictly decreasing function. An increase in the pollution stock P reduces utility, while an increase in adaptation capital D attenuates the utility reduction caused by pollution. The planner's problem is to maximize (8) subject to (5), (6), and (7).

Solving the problem by the Hamiltonian approach, we obtain the following equation

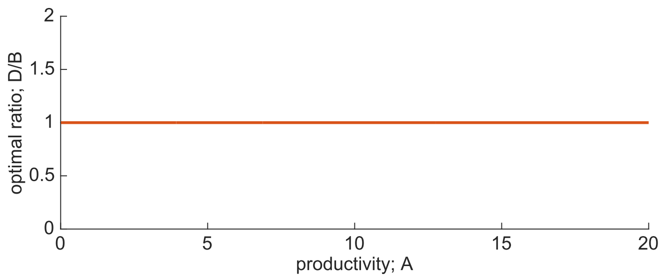

Fig. 4. Optimal ratio in Example 3.

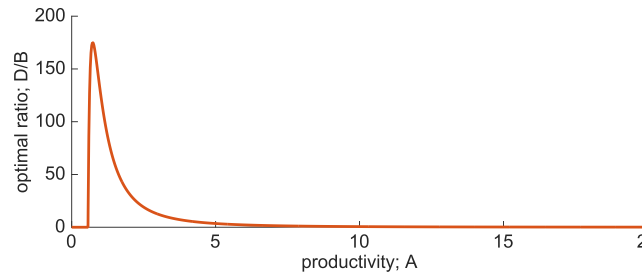

Fig. 5. Optimal ratio in Example 4.

$$-\frac{\eta'(D)}{\eta(D)} = -\varepsilon\frac{g'(B)}{g(B)}\frac{\nu'(P)}{\nu(P)}, \tag{9}$$

where $\varepsilon = \frac{\rho+\delta_D}{\rho+\delta_P}\delta_P$.[2] This equation is very similar to Equation (3). The difference is that the equation above has two additional terms, the coefficient ε and the ratio $\frac{\nu'(P)}{\nu(P)}$. The former appears because mitigation B is modeled as a flow, while adaptation D is modeled as a stock, and the latter appears because mitigation B is modeled to affect utility only indirectly, through reducing the pollution stock P.

We compute the optimal ratio numerically for three chosen examples, which have counterparts in examples in the Appendix. In all of the examples, the function ν is fixed as

$$\nu(P) = P^2\Big/2,$$

and the economic parameters are fixed as follows: $\alpha = 0.66$, $\rho = 0.01$, $\delta_P = 0.0002$, $\gamma = 0.16$.

Example 3. (**Constant ratio**). The return functions are given by

$$g(B) = B^{-\theta},$$

$$\eta(D) = D^{-\gamma},$$

where $\theta > 0$ and $\gamma > 0$ are parameters. Fig. 4 depicts the ratio for $\theta = 1$ and $\gamma = 1$.

Example 4. (**Ratio increasing for low level and decreasing for high level**). The return functions are given by

$$g(B) = B^{-1},$$

$$\eta(D) = \underline{\eta} + \left(\overline{\eta} - \underline{\eta}\right)e^{-aD},$$

where $\underline{\eta} > 0$, $\overline{\eta} > 0$, and $a > 0$ are parameters that satisfy $\underline{\eta} < \overline{\eta}$. This is the case analyzed in Bréchet et al. (2013). Fig. 5 depicts the ratio that is numerically calculated for $\underline{\eta} = 0.0025$, $\overline{\eta} = 0.003$, and $a = 0.005$.

Example 5. (**Ratio decreasing for low level and increasing for high level**). The return functions are given by

$$g(B) = \underline{g} + \left(\overline{g} - \underline{g}\right)e^{-bB},$$

$$\eta(D) = D^{-1},$$

here $\underline{g} > 0$, $\overline{g} > 0$, and $b > 0$ are parameters that satisfy $\underline{g} < \overline{g}$. Fig. 6 depicts the ratio that is numerically calculated for $\underline{g} = 0.00005$, $\overline{g} = 0.1$, and $b = 0.001$.

4.2. Zemel (2015)

In this model, there is no parameter that determines the amount of available resources and mitigation is modeled more implicitly than in the models that we have seen above. Although these features make it difficult to compare the model of Zemel (2015) with those above, the optimal mitigation and adaptation are linked by a similar equation to that in the simple model and that of Bréchet et al. (2013). Furthermore, we will see how the multiplicative form arises endogenously in this model.

Time is continuous and indexed by t. The horizon is infinite. At each moment t, the planner determines the production activity level $Y(t) \geq 0$ and adaptation investment $I(t) \in [0, \bar{I}]$. A unit of production activity yields a unit of consumption good and a unit of emissions, which contributes to increasing the pollution stock:

$$\dot{P}(t) = Y(t) - \delta_P P(t), \tag{10}$$

where $\delta_P > 0$ denotes the natural pollution decay rate. The adaptation investment increases adaptation capital $D(t)$, which evolves as

$$\dot{D}(t) = I(t) - \delta_D D(t), \tag{11}$$

where $\delta_D > 0$ denotes the depreciation rate, at a unit of utility cost. For a pair $(Y(t), I(t))$, the planner obtains a flow utility $u(Y(t)) - I(t)$. The pollution stock determines the risk of the occurrence of a disastrous event, which yields damage $\eta(D(t))$ in terms of utility, where η is a function that satisfies $\eta > 0$, $\eta' < 0$, and $\eta'' < 0$. The survival probability of the disastrous event $S(t)$ evolves according to

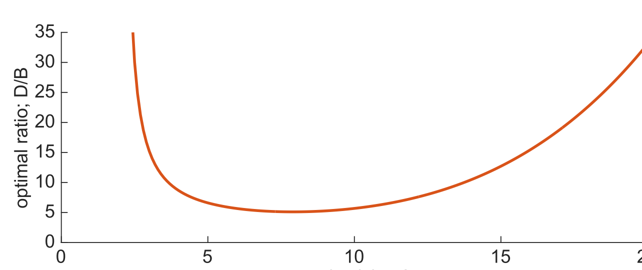

Fig. 6. Optimal ratio in Example 5.

[2] See the Appendix for the derivation of the equation.

$$\dot{S}(t) = -\nu(P(t))S(t), \tag{12}$$

where ν is a function that satisfies $\nu(0) = 0$, $\nu' > 0$, and $\nu'' \geq 0$. Let T denote the random time at which the disastrous event occurs. The optimization problem can be described through the principle of optimality:

$$V(P(s), D(s)) = \max E_s \left[\int_s^T e^{-\rho t}[u(Y(t)) - I(t)]dt + e^{-\rho T}(V(P(T), D(T))) \right], \tag{13}$$

subject to (10), (11), (12), $P(0) = P_0$, $S(0) = 1$, $D(0) = 0$, $Y(t) \geq 0$, and $I(t) \in [0, \bar{I}]$, where E_s is an expectation operator conditional on information up to s, and $\rho > 0$ is a discount factor.

Solving the problem by the dynamic programing, restricting our attention to steady states, we have

$$-\frac{\eta'(D)}{\eta(D)} = -\hat{\varepsilon}\frac{1}{u'(Y)}\frac{\nu'(P)}{\nu(P)}, \tag{14}$$

which is similar to Equations (3) and (9).[3] The coefficient $\hat{\varepsilon}$ appears because the two measures are modeled as stocks, and the term $\frac{1}{u'(Y)}$ appears because mitigation and adaptation have different impacts on utility: the shadow value of the former is $u'(Y)$, while that of the latter is 1.

5. Discussion

We displayed a set of return functions for mitigation and adaptation and examined the resulting relationship between the amount of available resource and optimal adaptation-mitigation ratio. A natural question would be which functional forms fit the reality.

For adaptation, three important qualitative features are discussed: (i) no damages are reduced with no adaptation; (ii) decreasing marginal returns of adaptation; and (iii) the infinite adaptation can reduce all damages. There seems to be a consensus about the first two features, and virtually all models in the literature assume them (e.g., AD-DICE, Bréchet et al. (2013), Ingham et al. (2013)). The third feature, which specifies the behavior of the right tail of the adaptation return function, is more controversial. Bréchet et al. (2013) and Chambwera et al. (2014) consider the other possibility that the infinite adaptation does not reduce all damages and Chambwera et al. (2014) calls the gap between the damages that adaptation can reduce and the whole damage the technology limits.

We do not actually need to know the size of damages the infinite adaptation would reduce; Rather, it is sufficient to know the size of damages would be reduced when all possible adaptation projects are conducted. After accumulation of evaluation of adaptation projects, some estimations would be available for such a number. To capture this feature, the formulation in Bréchet et al. (2013) is convenient. There, the function has the form

$$\eta(D) = \underline{\eta} + \left(\bar{\eta} - \underline{\eta}\right)f(D),$$

where $f(D) = \exp(-aD)$ and $a > 0$. This way of formulation can be applied to any functions f and convert them to functions that are bounded away from 0.

Another important feature of the adaptation return function is the marginal returns around 0: how effective small amount of adaptation investments are. Chambwera et al. (2014) discuss that there are some almost free adaptation measures (such as changing sowing dates in the agricultural sector) and returns of adaptation when the small amount of resource are invested to adaptation would be very high. Other works (e.g., Vermeulen et al. (2016), UNFCCC (2011)) report that adaptation plans such as flood and coastal erosion management options or climate-resilient agricultural development have the benefit-cost ratio that are higher than 5. In particular, Wang et al. (2016) conduct the cost-benefit analysis of measures for adapting Australian coastal residential buildings to future coastal inundation hazard and its estimated benefit is over \$4 billion at the costs which are a lower order of the benefits.[4]

These empirical results suggest that it is reasonable to assume that the adaptation return function is almost vertically-steeped near 0. The exponential form $\exp(-D)$ and the fraction form $\frac{1}{1+D}$, which is used in recent IAM models involving adaptation decisions, do not satisfy this condition. On the other hand, the power form $D^{-\gamma}$ and the composite form $\exp(-D^{\sigma})$ satisfy the condition. In particular, the latter form is convenient because it is in the form of the ratio of avoided damages, which is used in the IAM models.

Based on the discussion above, we formulate a model with specific functional forms for returns and provide a calibrated results. For mitigation return function, we employ an exponential specification following the framework of Golosov et al. (2014) and Schumacher (2016). They show that the specification approximates that in the DICE model well, which produces largely consistent results with those of the Energy Modeling Forum 22 exercise (Nordhaus, 2017). This choice sets the return function for mitigation as

$$g(B) = \exp\left[-\gamma\left(S(B) - \bar{S}\right)\right], \tag{15}$$

$$S(B) = \frac{\phi W}{1 + B}, \tag{16}$$

where $\gamma > 0$ is the elasticity parameter, $S(B)$ is the resulting atmospheric carbon level when mitigation investment is B, $\bar{S}$ is the pre-industrial atmospheric carbon level, ϕ is the parameter of production-emission ratio, and W is the world total income. As we discussed above, we use the adaptation return function of the composite form:

$$\eta(D) = \exp(-aD^{\sigma}) \tag{17}$$

where $a > 0$ and $D \in (0, 1)$ are parameters.

We choose the parameter values as follows. The estimated global carbon emission in 2015 is 36.2 billion ton (EC-JRC/PBL, 2017), which is converted to 9.86 gigaton carbon (GtC). The gross world product is 74.8 trillion 2015 US dollars. Accordingly, we set $W = 74.8$ and $\phi = 9.86/74.8$. Following Golosov et al. (2014), the damage elasticity parameter γ is set equal to 5.3×10^{-5}. The estimated pre-industrial level of atmospheric carbon is 590 GtC. These choice specifies the mitigation return function. Following de Bruin et al. (2009), we calibrate the adaptation return parameters, a and σ, with two conditions. The first condition restricts the share of

[3] See the Appendix for the derivation of the equation.

[4] ECONADAPT (2015), which overviews evidence from cost-benefit analyses of adaptation, reports that coastal areas are the sector for which cost-benefit analyses are accumulated the most. See also Watkiss (2015).

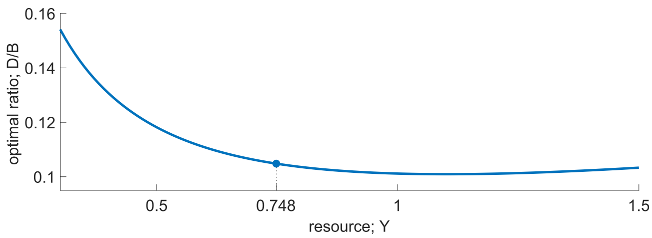

Fig. 7. Optimal ratio in the calibrated model.

adaptation costs in total damages equal to 25% (Tol et al., 1998). The second condition specifies the avoided damages to be 55% of the total. We apply these conditions to the model supposing that 1% of the total income is used for climate change policy. The resulting parameter values for the adaptation return function is $a = 0.598$ and $\sigma = 2.21 \times 10^{-5}$.

Fig. 7 shows the optimal ratio of adaptation to mitigation for different amounts of available resources. The dot on the optimal ratio curve represents the optimal ratio at the calibrated point. The result shows that, in contrast to the results in Schumacher (2016) or Bréchet et al. (2013), the concentration to mitigation does not arise at the optima. The existence of adaptation plans with high returns should attract some investment even when the resource is not abundant.

So far we discussed functional forms of mitigation and adaptation returns independently. That is, of course, not sufficient to specify the joint return function for mitigation and adaptation returns and obtain more useful insights about the optimal mixture. Empirical works in this direction, that is, works that provide estimations of returns to adaptation for various levels of mitigation investments and resulting climate change are required.

How robust the results from the IAMs such as the AD-DICE model or the AD-WITCH model are is an important question. de Bruin et al. (2009) compute the solution using two types of functional forms (power and fraction) and confirm that their result is not affected significantly.[5] Such a robustness check should be conducted in a more comprehensive way, applying other functional forms to other IAMs.

6. Conclusion

We have explored the optimal mitigation-adaptation ratio in a simple model and proposed an equation that links the optimal investments in the two measures. Using the equation, we have demonstrated that the relationship between the optimal ratio and amount of resources available can exhibit various patterns, according to the functional forms assumed for the returns to mitigation and adaptation. In other words, the basic assumptions in a mitigation-adaptation investment problem that returns are diminishing and that an increase in investment in one measure reduces the necessity of the other leave a high degree of freedom in the relationship.

We have demonstrated that this insight is useful for understanding more complicated models, such as Bréchet et al. (2013) and Zemel (2015), by showing that similar equations characterize the optimal ratio and displaying a variety of patterns of the relationship in our examples.

As noted in the model section, the multiplicative form of the utility function is an important assumption of our analysis. One possible interpretation is that, in the context in which it is reasonable to assume that mitigation determines the probability of the occurrence of a harmful event and adaptation determines the damage of it, the multiplicative form is simply a reduced form of the expected value calculation. In other contexts, it should be interpreted as simply a crude means of capturing the substitutability between mitigation and adaptation. We leave analyses with general dependence to future work.

Our results imply that it is difficult to reach a conclusion about the relationship between optimal ratio of mitigation and adaptation investment and amount of available resources only through theoretical approach and that it is a question that should be answered empirically. To achieve more desirable mitigation-adaptation investment ratio, we should collect information on returns to adaptation measures given various levels of mitigation investment. As discussed in Agrawala (2011), we have only limited results to answer the question.

Pindyck (2013) criticizes IAMs for various arbitrariness in modeling decisions, including the choice of functional forms. This article addresses a similar problem in mitigation-adaptation investment and describes how functional forms can affect the outcomes of models with more technical details in this specific context.

Appendix A. Proof of Proposition

Proof. The proof is constructive. Take an arbitrary function $\widehat{r}:(0,\infty)\to(0,\infty)$ that satisfies the inequality condition. Set $g(B) = 1/B$; then, it clearly is continuously differentiable, strictly decreasing, and strictly log-convex, and $F_g(B) = F_g^{-1}(B) = 1/B$. Set

$$\eta(D) = \exp\left(-\int_0^D \frac{\widehat{r}(y)}{y}dy\right).$$

Then, it is clearly continuously differentiable and strictly decreasing. Strict log-convexity is proven as follows:

$$\frac{d^2}{dD^2}\log\eta(D) = \frac{d^2}{dD^2}\left(-\int_0^D \frac{\widehat{r}(y)}{y}dy\right).$$

$$= -\frac{d}{dD}\left(\frac{\widehat{r}(D)}{D}\right)$$

$$= -\frac{1}{D^2}\left(\widehat{r}'(D)D - \widehat{r}(D)\right) > 0.$$

The last inequality directly follows from the inequality condition. Because

$$F_\eta(D) = \frac{\widehat{r}(D)}{D},$$

the existence of a pair (g,η) of our interest is proved. ∎

Appendix B. Examples

Example 6. **(Constant ratio).** The return functions are given by

[5] Our framework is similar to the AD-WITCH model than to the AD-DICE model in the sense that adaptation expenditure is made from the total resources. Instead, in the AD-DICE model, adaptation expenditures are made at costs in terms of damages.

$$g(B) = B^{-\theta},$$

$$\eta(D) = D^{-\gamma},$$

where $\theta > 0$ and $\gamma > 0$ are parameters. These functions are strictly decreasing, continuously differentiable, and strictly log-convex, and thus satisfy the assumptions. The functions F_g and $F_\eta$are expressed as

$$F_g(B) = \theta B^{-1},$$

$$F_\eta(D) = \gamma D^{-1}.$$

By solving

$$D^* + \theta\left[\gamma D^{*-1}\right]^{-1} = Y,$$

we obtain explicit solutions $D^*(Y) = \frac{\gamma}{\theta+\gamma} Y$ (and $B^*(Y) = \frac{\theta}{\theta+\gamma} Y$). The optimal ratio is

$$R(Y) \equiv \frac{D^*(Y)}{F_g^{-1}(F_\eta(D^*(Y)))} = \frac{\gamma}{\theta}.$$

Fig. B.8 depicts the function $R(Y)$ when $\theta = \gamma = 1$.

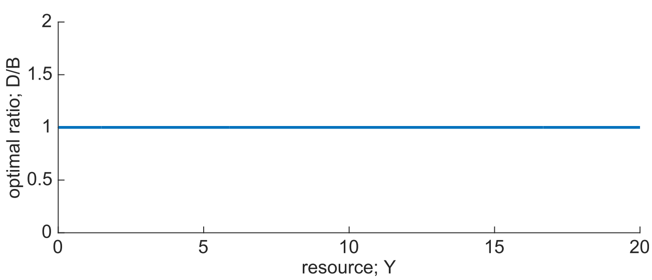

Fig. B.8. Optimal ratio in Example 6.

Example 7. **(Increasing ratio with boundary solution).** The return functions are given by

$$g(B) = B^{-\theta},$$

$$\eta(D) = e^{-aD},$$

where $\theta > 0$ and $a > 0$ are parameters. The function g satisfies all of the assumptions, but η satisfies only continuous differentiability and strict decreasingness. It is not strictly log-convex but only weakly log-convex. The KKT condition still characterizes the optimal solution and Lemma 1 holds. Because

$$-\frac{g'(B)}{g(B)} = \theta B^{-1},$$

$$-\frac{\eta'(D)}{\eta(D)} = a,$$

as long as $0 \le Y \le \theta/a$, the inequality

$$-\frac{\eta'(0)}{\eta(0)} \le -\frac{g'(Y)}{g(Y)}$$

holds and the optimal adaptation is at the boundary $D = 0$. For $Y > \theta/a$, the solution is interior, and by solving

$$D^* + \theta a^{-1} = Y$$

we obtain explicit solutions $D^* = Y - \theta a^{-1}$ and $B^* = \theta a^{-1}$. Therefore, the ratio is given by

$$R(Y) = \begin{cases} 0 & \text{for } Y \in (0, \theta/a], \\ \dfrac{Y - \theta/a}{\theta/a} & \text{for } Y \in (\theta/a, \infty). \end{cases}$$

Fig. B.9 depicts the function $R(Y)$ when $\theta = 5$ and $a = 1$.

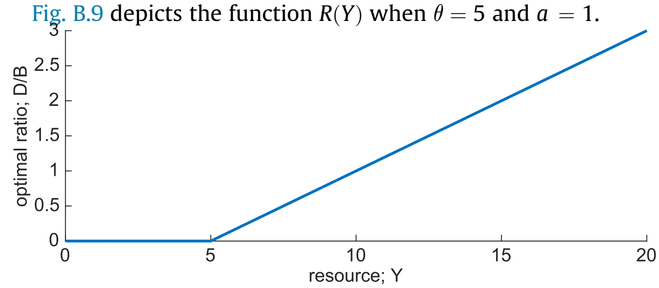

Fig. B.9. Optimal ratio in Example 7.

Example 8. **(Decreasing ratio with boundary solution).** This is simply a symmetric version of Example 7.The return functions are given by

$$g(B) = e^{-bB},$$

$$\eta(D) = D^{-\gamma},$$

where $b > 0$ and $\gamma > 0$ are parameters. The function η satisfies all of the assumptions, but g satisfies only continuous differentiability and strict decreasingness. It is not strictly log-convex but only weakly log-convex. As long as $0 \le Y \le \gamma/b$, the inequality

$$\gamma Y^{-1} \equiv -\frac{\eta'(Y)}{\eta(Y)} \ge -\frac{g'(0)}{g(0)} \equiv b$$

holds and the optimal mitigation is at the boundary $B = 0$. For $Y > \gamma/b$, the solution is interior, and by solving

$$\gamma/b + B^* = Y$$

we obtain explicit solutions $D^* = \gamma/b$ and $B^* = Y - \gamma/b$. Therefore, the ratio is given by

$$R(Y) = \begin{cases} \infty & \text{for } Y \in (0, \gamma/b], \\ \dfrac{\gamma/b}{Y - \gamma/b} & \text{for } Y \in (\gamma/b, \infty). \end{cases}$$

Fig. B.10 depicts the function $R(Y)$ when $\gamma = 5$ and $b = 1$.

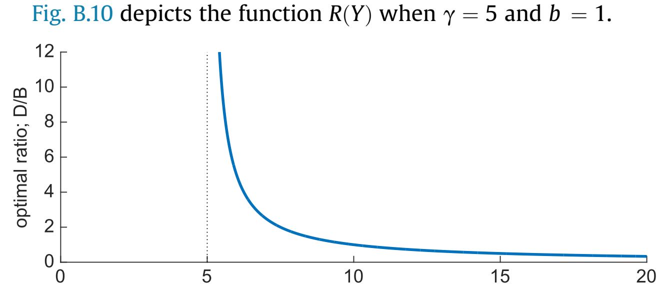

Fig. B.10. Optimal ratio in Example 8.

Example 9. **(Ratio decreasing for low level and increasing for high level).** This is a symmetric version of Example 2. The return functions are given by

$$g(B) = \underline{g} + \left(\overline{g} - \underline{g}\right)e^{-bB},$$

$$\eta(D) = D^{-1},$$

here $\underline{g} > 0$, $\overline{g} > 0$, and $b > 0$ are parameters that satisfy $\underline{g} < \overline{g}$. The functions g and η satisfy all of the assumptions. As long as $0 \leq Y \leq \frac{\overline{g}}{b\left(\overline{g}-\underline{g}\right)}$, the inequality

$$-\frac{\eta'(Y)}{\eta(Y)} \geq -\frac{g'(0)}{g(0)}$$

holds and the optimal adaptation is at the boundary $B = 0$. For $Y > \frac{\overline{g}}{b\left(\overline{g}-\underline{g}\right)}$, the solution is interior and characterized by

$$D^{*} + \frac{1}{b}\log\left[\frac{\left(\overline{g} - \underline{g}\right)}{\underline{g}} \frac{b - D^{*-1}}{D^{*-1}}\right] = Y.$$

To the best of our knowledge, this equation does not allow any explicit solution, and we investigate the shape of $R(Y)$ by investigating the shape of

$$\widehat{R}(D) \equiv \frac{D}{F_g^{-1}(F_\eta(D))} = D\frac{1}{b}\log\left[\frac{\left(\overline{g} - \underline{g}\right)}{\underline{g}} \frac{b - D^{*-1}}{D^{*-1}}\right]$$

and

$$\frac{d}{dD}\widehat{R}(D) = \frac{1}{b}\log\left[\frac{\overline{g} - \underline{g}}{\underline{g}} \frac{b - D^{-1}}{D^{-1}}\right] + \frac{1}{b - D^{-1}}.$$

This function is strictly increasing for $D = 1/b$, $\lim_{D\to 1/b}\frac{d}{dD}\widehat{R}(D) = -\infty$, and $\lim_{D\to\infty}\frac{d}{dD}\widehat{R}(D) = \infty$. Therefore, we can tell that R is increasing up to some level $\overline{Y}$, and decreasing beyond that level. Fig. B.11 depicts the function $R(Y)$ when $\underline{g} = 10$, $\overline{g} = 100$, and $b = 1$.

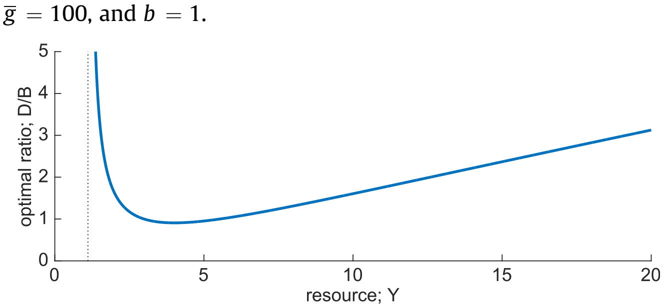

Fig. B.11. Optimal ratio in Example 9.

Example 10. **(Ratio monotone without boundary solution).** The return functions are given by

$$g(B) = \exp(-bB^{\pi}),$$

$$\eta(D) = \exp(-aD^{\sigma}),$$

where $\pi \in (0, 1)$ and $\sigma \in (0, 1)$ are parameters. The functions g and η satisfy all of the assumptions. Because

$$-\frac{\eta'(0)}{\eta(0)} = -\frac{g'(0)}{g(0)} = \infty,$$

the solution is always interior. The solution is characterized by

$$D^{*} + \left[\frac{\sigma}{\pi}D^{*\sigma-1}\right]^{\frac{1}{\pi-1}} = Y.$$

To the best of our knowledge, this equation does not allow any explicit solution, and we investigate the shape of $R(Y)$ by investigating the shape of

$$\widehat{R}(D) \equiv \frac{D}{F_g^{-1}(F_\eta(D))} = D\left[\frac{\sigma}{\pi}D^{\sigma-1}\right]^{-\frac{1}{\pi-1}} = \left[\frac{\sigma}{\pi}\right]^{\frac{1}{1-\pi}} D^{1-\frac{1-\sigma}{1-\pi}}.$$

Because

$$\frac{d}{dD}\widehat{R}(D) = \left[\frac{\sigma}{\pi}\right]^{\frac{1}{1-\pi}}\left[1 - \frac{1-\sigma}{1-\pi}\right]D^{-\frac{1-\sigma}{1-\pi}},$$

the ratio is globally

$$\begin{cases} \text{increasing} & \text{if } \sigma > \pi, \\ \text{constant} & \text{if } \sigma = \pi, \\ \text{decreasing} & \text{if } \sigma < \pi. \end{cases}$$

Fig. B.12 depicts the ratio $R(Y)$ when $a = b = 1$, $\pi = 0.5$, and $\sigma = 0.25$, and Fig. B.13 depicts the ratio $R(Y)$ when $a = b = 1$, $\pi = 0.25$, and $\sigma = 0.5$.

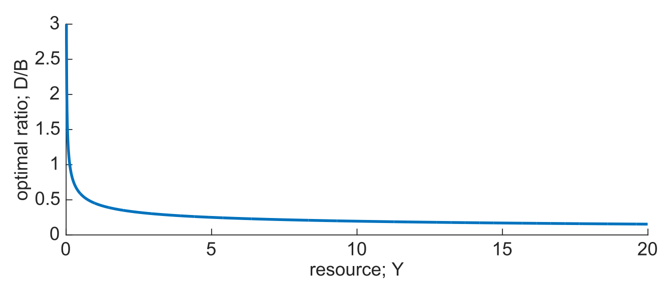

Fig. B.12. Optimal ratio in Example 10, when $a = b = 1$, $\pi = 0.5$, and $\sigma = 0.25$.

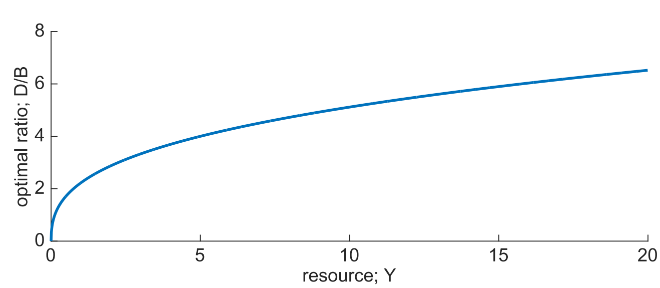

Fig. B.13. Optimal ratio in Example 10, when $a = b = 1$, $\pi = 0.25$, and $\sigma = 0.5$.

Example 11. The return functions are given by

$$g(B) = B^{-1},$$

$$\eta(D) = D^{-2}\exp\left(- \int_0^D \frac{\sin^2 y}{y^2} dy \right).$$

Then, g and η are continuously differentiable, strictly decreasing, and strictly log-convex. We have

$$\widehat{R}(D) \equiv \frac{D}{F_g^{-1}(F_\eta(D))} = \frac{D}{\left(\frac{1}{D}\left[\frac{\sin^2 D}{D}+2\right]\right)^{-1}} = \frac{\sin^2 D}{D}+2.$$

This function exhibits repetitive oscillation with decreasing amplitude, and thus the optimal ratio $R(Y)$ also exhibits such a pattern. Fig. B.14 displays the result of a numerical computation, which shows the actual shape of $R(Y)$.

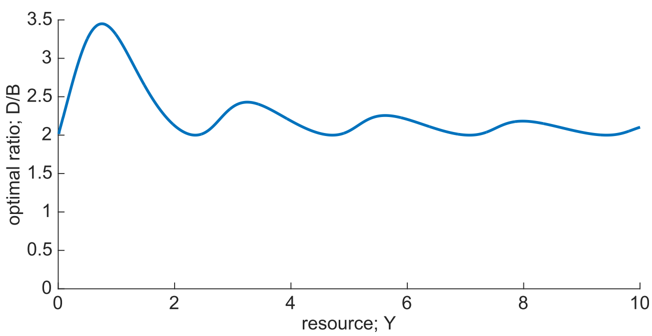

Fig. B.14. Optimal ratio $R(Y)$ in Example 11.

References

Agrawala, Shardul, September 2011. Adapting to climate change: costs, benefits, and modelling approaches. Int. Rev. Environ. Resour. Econ. 5 (3), 245–284. https://doi.org/10.1561/101.00000043. ISSN 19321473. http://www.nowpublishers.com/article/Details/IRERE-0043.

Agrawala, Shardul, Bosello, Francesco, Carraro, Carlo, Bruin, Kelly de, De Cian, Enrica, Dellink, Rob, Lanzi, Elisa, August 2010. Plan or React? Analysis of Adaptation Costs and Benefits Using Integrated Assessment Models. OECD Environment Working Papers, Organisation for Economic Co-operation and Development, Paris. http://www.oecd-ilibrary.org/content/workingpaper/5km975m3d5hb-en.

Barrage, Lint, 2015. Climate Change Adaptation vs. Mitigation: a Fiscal Perspective.

Berrang-Ford, Lea, Pearce, Tristan, Ford, James D., Jun 2015. Systematic review approaches for climate change adaptation research. Reg. Environ. Change 15 (5), 755–769. https://doi.org/10.1007/s10113-014-0708-7. ISSN 1436-378X. https://doi.org/10.1007/s10113-014-0708-7.

Bosello, Francesco, Carraro, Carlo, Cian, Enrica De, 2010. Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. Climate Change Econ. 1 (02), 71–92.

Bréchet, Thierry, Hritonenko, Natali, Yatsenko, Yuri, June 2013. Adaptation and mitigation in long-term climate policy. Environ. Resour. Econ. 55 (2), 217–243. https://doi.org/10.1007/s10640-012-9623-x. ISSN 0924-6460, 1573-1502. https://link.springer.com/article/10.1007/s10640-012-9623-x.

Bretschger, Lucas, Valente, Simone, 2011. Climate Change and Uneven Development*, 113(4), pp. 825–845. https://doi.org/10.1111/j.1467-9442.2011.01676.x. ISSN 1467-9442. http://onlinelibrary.wiley.com/doi/10.1111/j.1467-9442.2011.01676.x/abstract.

Buob, Seraina, Stephan, Gunter, 2011. To mitigate or to adapt: how to confront global climate change. Eur. J. Polit. Econ. 27 (1), 1–16. https://doi.org/10.1016/j.ejpoleco.2010.05.001. ISSN 0176-2680. http://www.sciencedirect.com/science/article/pii/S0176268010000297.

Chambwera, M., Heal, G., Dubeux, C., Hallegatte, S., Leclerc, L., Markandya, A., McCarl, B.A., Mechler, R., Neumann, J.E., April 2014. Chapter 17-Economics of adaptation. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the IPCC. Cambridge University Press.

de Bruin, Kelly C., Dellink, Rob B., Tol, Richard S.J., 2009. AD-DICE: an implementation of adaptation in the DICE model. Climatic Change 95 (1–2), 63–81.

de Bruin, Kelly Chloe, 2011. Distinguishing between Proactive (Stock) and Reactive (Flow) Adaptation. Available at SSRN 1854285.

Ebert, Udo, Welsch, Heinz, May 2012. Adaptation and mitigation in global pollution problems: economic impacts of productivity, sensitivity, and adaptive capacity. Environ. Resour. Econ. 52 (1), 49–64. https://doi.org/10.1007/s10640-011-9519-1. ISSN 1573-1502. https://doi.org/10.1007/s10640-011-9519-1.

EC-JRC/PBL, 2017. Edgar, version 4.3.2.

ECONADAPT, 2015. The Costs and Benefits of Adaptation; Results from the ECONADAPT Project. Technical report.

Felgenhauer, Tyler, Webster, Mort, Feb 2014. Modeling adaptation as a flow and stock decision with mitigation. Climatic Change 122 (4), 665–679. https://doi.org/10.1007/s10584-013-1016-9. ISSN 1573-1480. https://doi.org/10.1007/s10584-013-1016-9.

Golosov, Mikhail, Hassler, John, Krusell, Per, Tsyvinski, Aleh, 2014. Optimal taxes on fossil fuel in general equilibrium. Econometrica 82 (1), 41–88. ISSN 0012-9682. http://www.jstor.org/stable/24029171.

Heuson, Clemens, Peters, Wolfgang, Schwarze, Reimund, Topp, Anna-Katharina, Dec 2015. Investment and adaptation as commitment devices in climate politics. Environ. Resour. Econ. 62 (4), 769–790. https://doi.org/10.1007/s10640-015-9887-z. ISSN 1573-1502. https://doi.org/10.1007/s10640-015-9887-z.

Hope, Chris, Anderson, John, Wenman, Paul, 1993. Policy analysis of the greenhouse effect: an application of the page model. Energy Policy 21 (3), 327–338. ISSN 0301-4215. https://doi.org/10.1016/0301-4215(93)90253-C. http://www.sciencedirect.com/science/article/pii/030142159390253C. Policy modelling for global climate change.

Ingham, Alan, Ma, Jie, Ulph, Alistair M., 2013. Can adaptation and mitigation be complements? Climatic Change 120 (1–2), 39–53.

IPCC, 2007. Climate Change 2007:Fourth Assesment Report of the IPCC. Cambridge University Press.

Kane, Sally, Shogren, Jason, 2000. Linking adaptation and mitigation in climate change policy. Climatic Change 45 (1), 75–102.

Mendelsohn, Robert, Jun 2000. Efficient adaptation to climate change. Climatic Change 45 (3), 583–600. https://doi.org/10.1023/A:1005507810350. ISSN 1573-1480. https://doi.org/10.1023/A:1005507810350.

Nordhaus, William D., February 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. U. S. A. 114 (7), 1518–1523. https://doi.org/10.1073/pnas.1609244114. ISSN 0027-8424, 1091-6490. http://www.pnas.org/lookup/doi/10.1073/pnas.1609244114.

Pindyck, Robert S., 2013. Climate change policy: what do the models tell us? J. Econ. Lit. 51 (3), 860–872.

Schumacher, Ingmar, 2016. Climate Policy Must Favour Mitigation over Adaptation.

Shibata, Hirofumi, Winrich, J. Steven, 1983. Control of pollution when the offended defend themselves. Economica 50 (200), 425–437.

Tol, Richard S.J., Jun 2007. The double trade-off between adaptation and mitigation for sea level rise: an application of fund. Mitig. Adapt. Strategies Glob. Change 12 (5), 741–753. https://doi.org/10.1007/s11027-007-9097-2. ISSN 1573-1596. https://doi.org/10.1007/s11027-007-9097-2.

Tol, Richard S.J., Fankhauser, Samuel, Smith, Joel B., 1998. The Scope for Adaptation to Climate Change: what Can We Learn from the Impact Literature?, 8(2), pp. 109–123. https://doi.org/10.1016/S0959-3780(98)00004-1. ISSN 0959-3780. http://www.sciencedirect.com/science/article/pii/S0959378098000041.

Tol, Richard S.J., 2005. Adaptation and mitigation: trade-offs in substance and methods. Environ. Sci. Policy 8 (6), 572–578. ISSN 1462-9011. https://doi.org/10.1016/j.envsci.2005.06.011. http://www.sciencedirect.com/science/article/pii/S1462901105001061. Mitigation and Adaptation Strategies for Climate Change.

Tol, Richard S.J., Fankhauser, Samuel, Mar 1998. On the representation of impact in integrated assessment models of climate change. Environ. Model. Assess. 3 (1), 63–74. https://doi.org/10.1023/A:1019050503531. ISSN 1573-2967. https://doi.org/10.1023/A:1019050503531.

UNFCCC, 2011. Assessing the Costs and Benefits of Adaptation Options. Technical report. United Nations, Framework Convention on Climate Change.

Vermeulen, Sonja, Richards, Meryl, De Pinto, Alex, Ferrarese, Dino, aderach, Peter L., Lan, Le, Luckert, Marty, Mazzoli, Enrico, Plant, Laura, Rinaldi, Roberto, Stephenson, Jim, Watkiss, Paul, 2016. The Economic Advantage: Assessing the Value of Climate-change Actions in Agriculture. Technical report. International Fund for Agricultural Development. https://cgspace.cgiar.org/handle/10568/77628.

Wang, Chi-Hsiang, Baynes, Tim, McFallan, Stephen, West, Jim, Khoo, Yong Bing, Wang, Xiaoming, Quezada, George, Mazouz, Salim, Herr, Alexander, Matthew Beaty, R., Langston, Art, Li, Yun, Lau, Kwok Wai, Hatfield-Dodds, Steve, Stafford-Smith, Mark, Waring, Adrian, April 2016. Rising tides: adaptation policy alternatives for coastal residential buildings in Australia. Struct. Infrastruct. Eng. 12 (4), 463–476. https://doi.org/10.1080/15732479.2015.1020500. ISSN 1573-2479.

Watkiss, Paul, 2015. A Review of the Economics of Adaptation and Climate-resilient Development. Technical report, Grantham Research Institute on climate change and the environment.

Zehaie, Ficre, May 2009. The timing and strategic role of self-protection. Environ. Resour. Econ. 44 (3), 337. https://doi.org/10.1007/s10640-009-9289-1. ISSN 1573-1502.

Zemel, Amos, 2015. Adaptation, mitigation and risk: an analytic approach. J. Econ. Dynam. Control 51, 133–147.